LAWRENCE LIVERMORE NATIONAL LABORATORY

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Mach-Zehnder Detector System Issues and Enhancements for use on the NIF DANTE X-Ray Diagnostic

B. V. Beeman, A. C. Carpenter, J. R. Kimbrough, T. J. Clancy, R. Chow, E. Bond, Z. Zayas-Rivera, P. Bell, J. Celeste, A. G. MacPhee, W. Widmann, T. Golod, E. K. Miller, R. Q. Abbott, K. K. Lee, J. C. Peterson, S. M. Gordoni, J. J. Buckley, W. R. Donaldson

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1. Unstable light levels or bias point incorrect?

The transfer function of the Mach-Zehnder modulator is sinusoidal; a quasi-DC bias voltage is applied to control the MZ operating or bias point. Typically the 50% transmission point is chosen as this is the point of maximum sensitivity for these devices; other bias points are available for different applications. A bias controller is used to automatically determine the bias voltage required to maintain the bias point, compensating for any drift due to thermal gradients in the Mach-Zehnder.

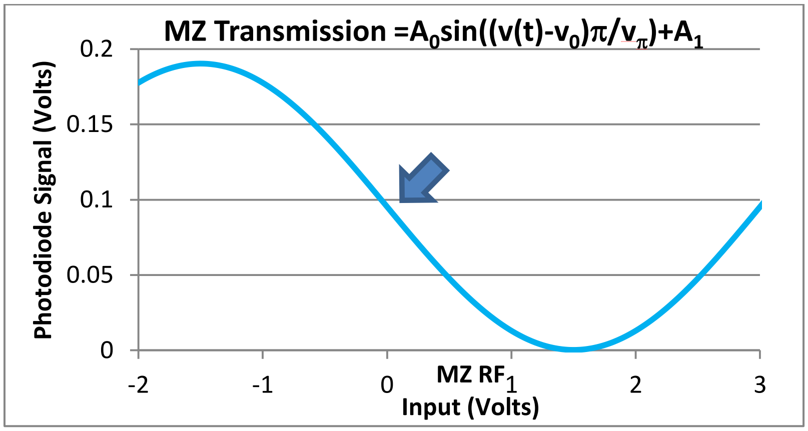

Figure 2: Mach-Zehnder transfer function, (-)50% transmission point indicated

The bias voltage (and bias point) during the short (100ps – 20ns) target shot is stable and appears as a DC level preceding any shot data. However, this level before the shot data is affected by multiple factors not just the bias point including: system losses, laser output power variations, and the actual bias point of the Mach-Zehnder.

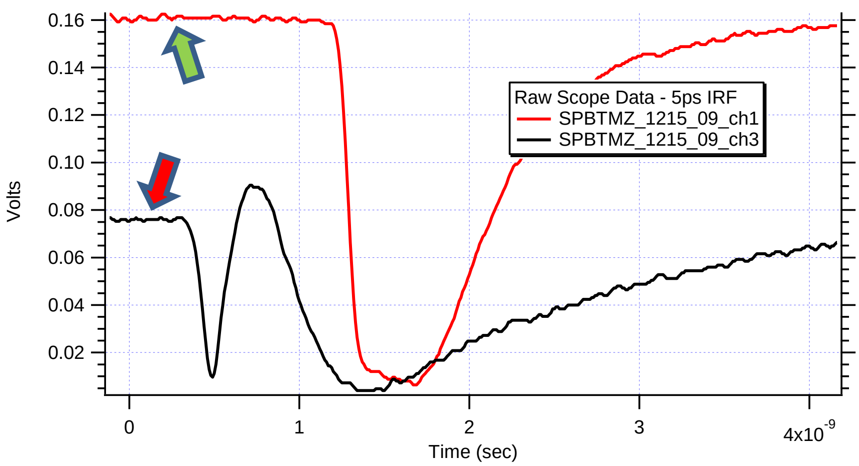

Figure 3: Black trace MZ3 biased at 50% transmission, Red trace MZ1 biased at 100% transmission

In Figure 3 both Mach-Zehnders had been adjusted such that at maximum transmission the DC level observed on the scope should have been 0.16v. The black trace with its MZ set for 50% transmission should have been at 0.08v. It is impossible to tell if the overall light level had decreased, or if the bias controller had caused a slight change in the bias point. Some amount of difference between the measured and ideal DC level is due to the operation of the type of bias controller deployed and can be accounted for as described below for dither based units.

1.1. A case study in system troubleshooting and mitigation suggestions

The largest issue we have experienced was eventually isolated to a failure of the internal fiber launch of the 100mW lasers. Trouble shooting was complicated as it was difficult to tell from the instrumentation if there was a bias point error, laser power fluctuation, or a system throughput issue. This prompted the development of the ramp based bias controller with a closed loop variable optical attenuator controller included; these are discussed in the bias controller section below.

The problem manifested itself as a large and inconsistent DC offset observed on the scope during the pre-shot dry run. Below are possible areas of concern and associated mitigations:

Possible cause of DC level shift	Mitigation or measurement technique
• **System throughput variations due to temperature or polarization drift**	• Use Polarizing (PZ) fiber jumpers between lasers and Mach-Zehnders • Minimize opening of temperature controlled racks

• **Bias point not controlled adequately**	• Verify with pulsed dry-run signal
	  ○ Optimize amplitude to only wrap once for clarity in interpretation of data
	• Increase dither amplitude for more accurate final (average) value
	  ○ The disadvantage to this approach is larger dither causes larger instantaneous errors

• **Laser diode failure**	• Compare laser diode current to specification • Inspect rear facet power monitor of laser diode
• **Laser module failure**	• Measure laser output directly at output fiber over the entire range using fixed value optical attenuators to remove ambiguity.
• **Laser power polarization dependency**	• Fiber coupled polarimeter measurements at MZ input

• **Residual amplitude variations from multiple effects (temperature, polarization, etc.)**	• Closed loop laser power control
	  ○ Software control of laser power level
	    ▪ More discussion below
	  ○ Hardware control of variable optical attenuator (VOA)

Table 1: Possible cause of observed DC light level shift and possible mitigations

1.2. Software control of laser power level

A control loop has been implemented to adjust the laser power setting based upon the observed DC level on the system scope. During the deployment of this capability it was observed the DC level was neither repeatable nor linear with changes to the requested laser power. Direct measurements of the laser output confirmed a fault within the laser diode package regardless of the rear facet or laser current readings. Laser power dependent polarization has recently been observed offline which could compromise this approach, however the power changes are small and the polarization changes may not be significant in this case, further investigation is ongoing.

1.3. Manufacture confirms (and repairs) faulty lasers

The manufacture confirmed our findings that rear facet and laser current indicated a good laser diode and were within spec. They opened the hermetically sealed package and discovered the internal fiber was badly burned. Careful examination of their process and production line devices lead them to believe there was a contamination issue on the face of the fiber after final assembly. After modification of their inspection and cleaning protocols no more lasers have failed, and the manufacture has repaired or verified operationally that all our lasers are 100mw capable.

2. Bias Controllers - Bias point and voltage determination

2.1 Dither based units

All the bias controllers deployed to date are based upon a commercial unit which relies upon the examination of harmonics of a relatively low frequency tone impressed upon the bias input of the MZs. This tone (~1kHz) causes the light level output to "dither" about the requested bias point, thus by design the bias point will not be at exactly the requested value except at 1 point during the dither period, which is not synchronized with the laser shot.

The primary method to minimize the effect of dithering the bias voltage is to keep the bias tone amplitude to ~1% of Vpi (voltage required for one pi output phase variation). Operationally a pulsed dry run signal of sufficient amplitude to drive the MZs from 0-100% transmission is switched into the input as a functional test in preparation for shots and is used to verify DC offset and bias point. Due to operational protocol for the NIF this dry run test can only occur 15-30min before the shot and is not definitive of conditions at shot time. Finally at shot time the dither is turned off approximately one second before the shot, a residual offset has still been observed however.

The two primary disadvantages are there is no indication of the accuracy of the actual bias point versus requested bias point and these controllers take several minutes to lock and stabilize. Lock time is dependent on dither amplitude; less amplitude corresponds to longer lock time and less accuracy of the lock. Limited bias voltage range is available relative to the Vpi of the Mach-Zehnders. Thus in order to achieve the desired bias point the output amplifier might run close to its maximum value. If the MZ bias point drifts requiring a bias voltage beyond the max output voltage the controller must be monitored and reset by the external computer. However the bias voltage cannot be reset near shot time due to the long lock time.

2.2 Ramp based unit (new)

A bias controller has been developed which does not utilize a dither to determine the bias point. Instead a voltage ramp is applied to the bias input and mapped to the corresponding light output. The primary advantage is this allows decoupling of bias point and light level control – very important for trouble shooting. In addition each 5 second cycle provides minimum and maximum transmission values enabling verification of the bias point by comparing the correction level to the ramp derived information. This continuous operation at five second intervals insures a valid bias point at shot time.

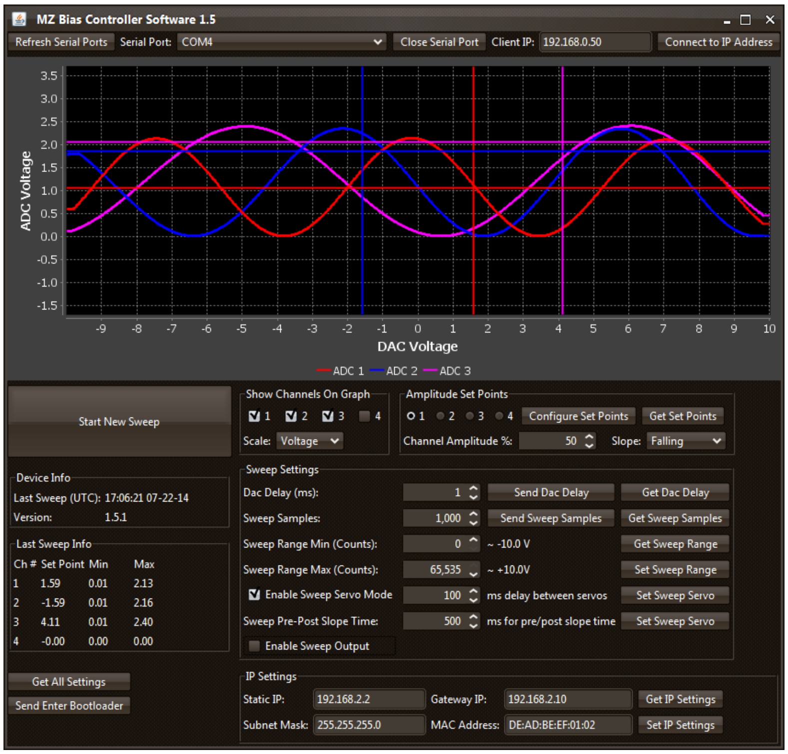

Figure 4: Mach-Zehnder Ramp based bias control User Interface

The display and parameter control of the new ramp based bias controller is depicted in Figure 4. The lower axis of the graph is the applied bias voltage (not including the external +/-18v amplifier) with the 3 sinusoid responses of the Mach-Zehnders plotted as a function of the applied bias voltage. Bias point in this modality is the percent transmission either on the rising or falling slope of the response curve. The horizontal and vertical lines indicate the transmission levels and the voltages required to obtain the requested "Amplitude Set Point". Summary information from the last sweep is in the lower left.

The bias points for this sweep were set to: Ch1 50% Falling slope, Ch2 83.5% Falling slope, Ch3 83.5% Rising slope. The derived corresponding bias voltages were, 1.59, -1.59, and 4.11 volts.

2.3 Mach-Zehnder nuances which had to be overcome:

Mach-Zehnder modulators are multi-GHz devices which can accurately follow signals with a rise time <50ps on their Rf input port. However, the bias voltage is applied to a separate "bias" port with unique properties. The bias port will respond to a multi kHz signal, however due to internal structure they have a settling time of several seconds. We limit the rate of change of large bias voltage changes and continuously correct the observed output light level, corresponding to the bias point of the Mach-Zehnder, with small bias voltage adjustments for ~3.5seconds (adjustable) before activating the variable optical attenuator. The VOA adjusts the final light level using a predetermined setpoint, but it does not affect the bias point of the Mach-Zehnder.

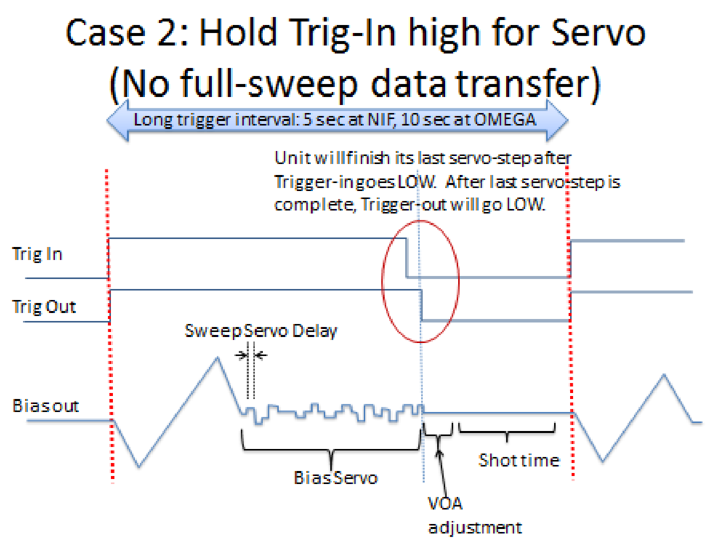

Figure 5: Method 2 - Continuous servo correction (VOA = Variable Optical Attenuator)

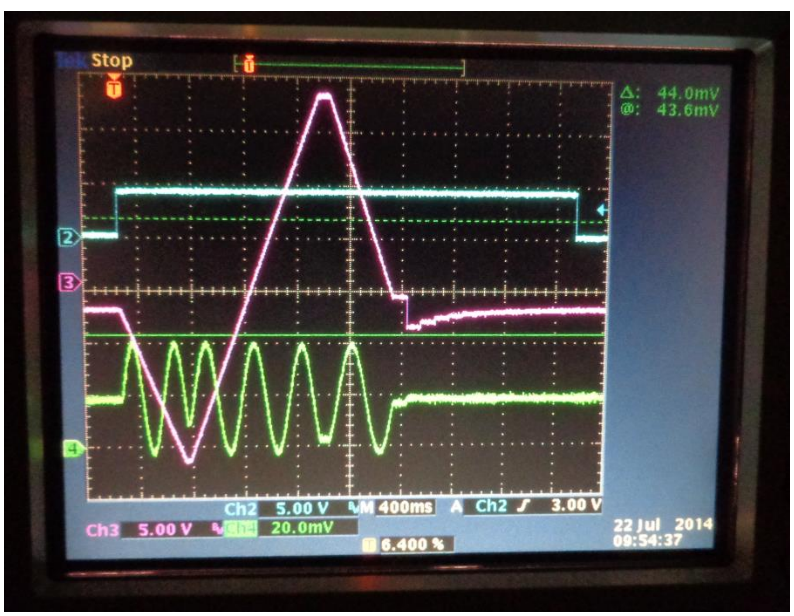

Figure 6: Trigger (2 - blue), Bias Voltage Ramp (3 - pink), and Filtered MZ Response (4 - green)

3 Conclusion

The best design practices are to separate the Mach-Zehnder bias point and light level controls along with optically amplifying the output signal from the Mach-Zehnder. In setting the bias point a ramp bias control is preferred over a dithering control; polarizing (PZ) fiber is better than polarization maintaining (PM) fiber to bring the light from the laser to the Mach-Zehnder. Amplifying the Mach-Zehnder optical output with a fiber amplifier (EDFA) requires both an optical input power high enough to overcome amplified spontaneous emission (ASE) and an optical filter to remove the residual ASE from the EDFA output.

In NIF, operations personal on different shifts operate the Mach-Zehnder system. The best operational practices are to have a simple operating procedure and a standard data analysis methodology that clearly shows the final expected waveform. The operating procedure covers, in addition to the standard start up and shut down, what to do in anticipated off normal operating conditions. The same data analysis methodology covers both system dry operating modes and actual shot data. This approach reduces operator errors.

While not specifically addressed in this paper, calibration of the Mach-Zehnders is required with the best results to date having been obtained using a temporal calibration, in this case a 45ps rise time pulse with a 15ns flat duration. [2]. A different approached being investigated is direct frequency domain characterization using a Vector Network Analyzer.

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